

K Band Microlensing of the Inner Galaxy

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Abstract

Microlensing searches toward the inner galaxy ($|l|, |b| \leq 22'.5$) have several major advantages. First, the event rate is strongly dominated by bulge-bulge lensing events where both the source and lens lie in the bulge. Second, these bulge-bulge events have very short time scales $t_e \sim 2$ days and are therefore easily distinguished from the less frequent and much longer bulge-disk and disk-disk events. Third, since the optical depth is similar to that at higher impact parameters, while the events are shorter, the event rate is high $\Gamma \sim 3 \times 10^{-7} \text{day}^{-1}$. Fourth, because the Einstein rings are small, $r_e \sim 5 \times 10^{12} \text{cm}$, and the source stars are large $r_s \gtrsim 10^{12} \text{cm}$, the lens will transit the face of the source for a significant fraction ($\sim 20\%$) of events. For these transit events it will often be possible to measure a second lens parameter, the angular Einstein radius (or proper motion). In addition to the bulge-bulge events, the optical depth of the disk is ~ 7 times larger toward the inner Galaxy than toward Baade's Window. A microlensing search toward the inner Galaxy can be carried out by making frequent ($\sim 4 \text{day}^{-1}$) K band images of a large area $\sim 0.5 \text{deg}^2$ to a depth of $K \sim 16$, and hence requires either a 1024^2 infrared array on a dedicated 2m telescope or four such arrays on a 1m telescope.

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1. Introduction

Microlensing searches toward the inner Galaxy in K band could help constrain the mass spectrum of the lensing objects now being detected at a rapid rate in ongoing microlensing searches. Lensing searches toward the inner Galaxy $\lesssim 30'$ from the Galactic center possess several unique features. Most notably, the events due to bulge lenses have very short ~ 2 day time scales, so they can be clearly distinguished from the much longer events due to disk lenses. Hence, an inner-Galaxy microlensing search can provide information that can clarify the major puzzles arising from current observations along lines of sight at $\sim 4^\circ$ from the Galactic center. Because of high extinction, this search can be carried out only in the K band.

Optical microlensing searches toward the Galactic bulge by Alcock et al. (1994 MACHO) and Udalski et al. (1994 OGLE) have detected more than 50 candidate events to date. The event rate is substantially greater than was anticipated by Paczyński (1991) and Griest et al. (1991) when they originally proposed the experiment as a method to probe the mass distribution of the Galactic disk. Bennett et al. (1994) estimate the mean optical depth toward fields near Baade's Window to be $\tau \sim 3 \times 10^{-6}$, more than five times higher than that expected from the disk. Kiraga & Paczyński (1994) pointed out that at least some of this shortfall could be accounted for by the 'standard' Kent (1992) model of the Galactic bulge with a mass $M_{bul} \sim 1.2 \times 10^{10} M_\odot$, which yields an optical depth $\tau_{bul} \sim 0.7 \times 10^{-6}$ in addition to that due to the disk. Paczyński et al. (1994) suggested that a triaxial Galactic bulge could substantially enhance the lensing rate. Han & Gould (1994) used the virial theorem to estimate the mass of an elongated bulge as modeled by Dwek et al. (1994) on the basis of data from the *Cosmic Background Explorer* (COBE). They found $M_{bul} \sim 1.8 \times 10^{10} M_\odot$ and $\tau_{bul} \sim 1.3 \times 10^{-6}$. Zhao, Spergel, & Rich (1995) obtained a similar result from a more detailed model. Blum (1994) pointed out that Han & Gould had neglected an important term related to figure rotation in the virial equation. He derived a further upward revision to as much

as $M_{bul} \sim 3.2 \times 10^{10} M_{\odot}$ with corresponding optical depth $\tau_{bul} \sim 2.3 \times 10^{-6}$. Note that Blum's estimate would imply that $\sim 38\%$ of the mass of the Galaxy interior to the solar orbit is in the bulge, and requires a mass-to-light ratio for the bulge of $M/L_V \sim 16$ (see Binney & Tremaine 1987).

These rapidly escalating estimates of the bulge mass and mass-to-light ratio raise the question of what the bulge is made of. In particular, one would like to know the spectrum of lens masses, M . The lensing events observed to date are of limited help in resolving this question for two reasons. First, the only information available about the events is their time scale, t_e . While this quantity generally scales $\propto M^{1/2}$, the mass associated with individual events can be estimated only to within an order of magnitude (Griest et al. 1991). Second, and greatly complicating the first problem, it is not known whether any individual lens that is detected is in the bulge or in the Galactic disk. The two classes of events have very similar time scales (Han & Gould 1994). Furthermore, as pointed out by Bennett et al. (1994), the optical depth appears to rise rapidly as one approaches the Galactic plane, perhaps indicating that a considerable fraction of all events are due to disk lenses. One would like to be able to examine a clean sample of bulge lenses.

Here I show that bulge lenses in the inner Galaxy present such a clean sample. Unlike the lenses found at higher impact parameter, these objects give rise to very short events that can easily be distinguished from foreground disk lenses. In particular, the low-mass lenses which give rise to the shortest events are especially easy to recognize. Moreover, for a large fraction ($\sim 20\%$) of these inner-Galaxy events, the lens will transit the source, making it possible to measure the Einstein Ring radius. These measurements can help further constrain the mass spectrum. A K band lensing search of the inner Galaxy can therefore yield important clues about the mass spectrum of the bulge which are not available from data taken along other lines of sight.

2. Microlensing By An Isothermal Sphere

In order to illustrate the fundamental features of microlensing toward the inner Galaxy, I analyze a simplified model. I assume that the lenses are distributed in a singular isothermal sphere with

$$\rho(r) = \frac{v_{\text{rot}}^2}{4\pi G r^2}, \quad (2.1)$$

where v_{rot} is the circular rotation speed which characterizes the density distribution. The Einstein ring radius is given by $r_e = (4GMd_{\text{ol}}d_{\text{ls}}/c^2d_{\text{os}})^{1/2}$ where d_{ol} , d_{ls} , and d_{os} are the distances between the observer, source, and lens. I assume that the lens lies close to the source, $d_{\text{ls}} \ll d_{\text{os}}$, so that

$$r_e = \sqrt{\frac{4GMd_{\text{ls}}}{c^2}}. \quad (2.2)$$

Finally I assume that the source lies exactly at the distance of the Galactic center, $d_{\text{os}} = R_0$. This last assumption introduces some distortion into the final result which I discuss below. However, it also makes the problem analytically tractable and so greatly facilitates the discussion.

Let $t_e = r_e/v$ be the characteristic time of the event, where v is the (two-dimensional) transverse speed of the lens relative to the observer-source line of sight. If both the sources and lenses have Gaussian velocity distributions $f(u_x, u_y) = (\pi v_{\text{rot}}^2)^{-1} \exp[-(u_x^2 + u_y^2)/v_{\text{rot}}^2]$, then the relative speed distribution is

$$f(v)dv = \frac{v}{v_{\text{rot}}^2} \exp\left(-\frac{v^2}{2v_{\text{rot}}^2}\right)dv. \quad (2.3)$$

The cross section to lensing is $2r_e$, so that the event rate for fixed lens mass M and for event times $t'_e < t_e$ is

$$\Gamma(t_e) = \int_0^\infty dd_{\text{ls}} 2r_e(d_{\text{ls}}, M) \frac{\rho(d_{\text{ls}})}{M} \int_{r_e/t_e}^\infty dv v f(v). \quad (2.4)$$

Hence, the differential rate is

$$\frac{d\Gamma}{dt_e} = \frac{4}{\pi} \frac{v_{\text{rot}}^2}{c^2} t_e^{-2} \int_0^\infty dz \frac{z^2}{z^2 + (t_b/t_e)^4} \exp(-z), \quad (2.5)$$

where z is a dummy variable,

$$t_b \equiv \frac{(2GMb)^{1/2}}{v_{\text{rot}} c} = 1.7 \text{ day} \left(\frac{M}{0.2 M_\odot} \right)^{1/2} \left(\frac{b}{50 \text{ pc}} \right)^{1/2} \left(\frac{v_{\text{rot}}}{200 \text{ km s}^{-1}} \right)^{-1}, \quad (2.6)$$

and b is the impact parameter to the Galactic center. The total event rate is

$$\Gamma = \sqrt{\frac{\pi}{2}} \frac{v_{\text{rot}}^2}{c^2} t_b^{-1} = 3 \times 10^{-7} \text{ day}^{-1} \left(\frac{M}{0.2 M_\odot} \right)^{-1/2} \left(\frac{b}{50 \text{ pc}} \right)^{-1/2} \left(\frac{v_{\text{rot}}}{200 \text{ km s}^{-1}} \right)^3. \quad (2.7)$$

In the two limits, the rate is

$$\frac{d\Gamma}{dt_e} = \frac{8}{\pi} \frac{v_{\text{rot}}^2}{c^2} \frac{t_e^2}{t_b^4} \quad (t_e \ll t_b), \quad (2.8)$$

and

$$\frac{d\Gamma}{dt_e} = \frac{4}{\pi} \frac{v_{\text{rot}}^2}{c^2} t_e^{-2} \quad (t_e \gg t_b). \quad (2.9)$$

The optical depth associated with these lensing rates is formally infinite because the range of the d_{ls} integration has been extended to infinity. In practice, this range is cut off at some radius R_c which is the shorter of the physical extent of the isothermal bulge or the distance $d_{\text{ls}} \sim R_0/2$ where equation (2.2) breaks down. The optical depth is then $\tau \sim (v_{\text{rot}}^2/c^2) \ln(R_c/b) \sim 1.5 \times 10^{-6}$.

3. Discussion

The above calculation shows that lensing events observed toward the inner Galaxy have two notable features: they are much shorter and more plentiful than bulge-bulge events observed toward optical windows at high impact parameter such as Baade’s Window ($b \sim 500$ pc). The fact that the events are short makes them easy to distinguish from lensing of bulge or disk stars by disk lenses (disk-bulge and disk-disk events respectively). By contrast, the time scales of bulge-bulge and disk-bulge events seen toward Baade’s Window are very similar, making it impossible to distinguish between the two by measuring t_e (Han & Gould 1994). Observations toward Baade’s Window and similar fields show a noticeable absence of short events $t_e < 6$ days, implying in particular that disk-bulge events must typically be longer than this limit. Hence, events observed toward the inner Galaxy with time scales ~ 2 days could be catalogued as bulge-bulge events with high confidence. Thus, the mass spectrum of bulge objects could be estimated without worrying about disk contamination.

The high event rate means that good statistics could be obtained over a few bulge seasons, in spite of the fact that it would be possible to monitor only $\sim 10^6$ stars in the inner Galaxy (see § 4). During a six-month season, one could expect to observe ~ 50 events.

The event rate from disk-bulge events would be lower than the bulge-bulge rate, but would still be very significant. At present, there is considerable debate over what fraction of the events seen toward Baade’s Window and similar fields is due to disk lenses. Paczyński (1991) and Griest et al. (1991) originally predicted an optical depth in this directions of $\sim 5 \times 10^{-7}$. However, Alcock et al. (1994) and Bennett et al. (1994) have speculated that the disk may be more massive than the standard ‘no missing mass’ disk on which these predictions were based. Regardless of the exact normalization or the functional form of the disk, one can be certain that the optical depth due to disk objects is higher toward the Galactic center than toward Baade’s Window. For example, for an exponential disk with scale height

$h \sim 325$ pc and scale length $H \sim 3000$ pc, the optical depth is a factor ~ 7 higher. See e.g., Griest et al. (1991). Thus, the inner-Galaxy fields would provide a rich source of information about disk microlensing. Since these events would typically be much longer than the bulge-bulge events, the disk-bulge events could generally be recognized as such.

Finally, for a significant fraction of the bulge-bulge events, the lens would transit the source, making it possible to measure the size of the angular Einstein ring, $\theta_e = r_e/d_{\text{ol}}$ (Gould 1994; Nemiroff & Wickramasinghe 1994). The cross section for such transit events is $2r_s$ where r_s is the radius of the source star. Hence, the rate for an ensemble of source stars is

$$\Gamma_{\text{tran}} = 2 \langle v \rangle \langle r_s \rangle \int_0^\infty dd_{\text{ls}} \frac{\rho(d_{\text{ls}}, M)}{M} = \sqrt{2\pi} \frac{v_{\text{rot}}^3}{8GMb} \langle r_s \rangle, \quad (3.1)$$

where $\langle r_s \rangle$ is the mean radius of the source stars. Comparison with equation (2.7) shows that a fraction,

$$\frac{\Gamma_{\text{tran}}}{\Gamma} = \frac{\langle r_s \rangle c}{(8GMb)^{1/2}}, \quad (3.2)$$

of the events would be transits. For typical numbers, $M = 0.2 M_\odot$, $b = 50$ pc, $\langle r_s \rangle = 22 R_\odot$ (see § 4), this fraction is $\sim 26\%$. Because $d_{\text{ol}} \sim d_{\text{os}}$, measurement of θ_e yields the product Md_{ls} . This information in conjunction with the measurement of t_e can help constrain the mass spectrum.

The entire analysis given here has assumed that the sources lie exactly at the midpoint of the lens density distribution. Realistically, one expects that the sources will be distributed as the lenses. I have elsewhere shown that this approximation leads to an underestimate of the optical depth by a factor $\alpha = \int_0^\infty dz[1 - F(z)] / \int_0^\infty dz[1 - F^2(z)]$ where $F(z)$ is the cumulative distribution of sources as a function of distance z from the midpoint of the distribution (Gould 1995). The size of this effect ranges from $2/3 \lesssim \alpha \lesssim 3/4$. It arises because the

characteristic distances d_{ls} are typically underestimated by a factor α . For this reason, the effect of including a realistic distribution is to increase the typical event times by $\alpha^{-1/2}$ and to increase the event rate by a similar amount. Hence, for present purposes one should simply scale all rates and time scales given in equations (2.5)-(2.9) upward by ~ 1.2 . Similarly, equation (3.2) should be reduced by a factor ~ 1.2 .

4. Practical Requirements

The inner Galaxy is heavily obscured, with visual extinction $A_V \sim 20$ –30 in most areas and much higher values in isolated spots. Thus K band photometry is essential to any microlensing search of this region. To make my estimates of the requirements of such a search, I assume $A_V = 30$ over 80% of the region and $A_V = \infty$ over the rest. I assume 1.''5 seeing and scale from the experience of the MACHO group (D. Bennett 1994, private communication) that in their crowding-limited fields they are able to monitor 10^6 stars deg^{-2} in 2.'' seeing with 0.''6 pixels. I infer that in crowding-limited K band images, one could resolve 1.1×10^6 stars in a 45' square field imaged with 0.''45 pixels. Allowing for total obscuration over 20% of the field, this is still 9×10^5 stars. The area could be covered in 36 exposures of a 1024^2 infrared array.

To find the crowding limit, I normalize the K band luminosity function from Baade's Window (G. Tiede and J. Frogel 1994, private communication) to the bright K-band counts of an inner-Galaxy field with measured extinction $A_K = 2$ (J. Frogel 1994, private communication) and find that there are $\sim 2 \times 10^6 \text{ deg}^{-2}$ stars to $K_0 \sim 13$. Hence, the exposures must reach $K = 16$ to achieve the crowding limit at the assumed $A_K = 3$ and 1.''5 seeing.

For average conditions of a Chilean winter ($K_{\text{sky}} \sim 13 \text{ mag arcsec}^{-2}$), a $K=19.5$ source contained within 1 arcsec^2 has signal to noise 10 in 35 minutes of exposure on a 1.8 m telescope (J. Frogel 1994, private communication). Scaling from this experience, I estimate that an isolated $K = 16$ star can be photometered with

accuracy $\sim 3.5\%$ with a 10 minute exposure on a 1 m telescope. This is similar to the typical signal to noise achieved by MACHO at the crowding limit in their fields in the Large Magellanic Clouds (LMC). I conclude that 10 minute exposures would suffice to obtain the $\sim 10\%$ photometry typically achieved by MACHO in their crowded LMC fields.

A mosaic of 4 1024^2 arrays mounted on a 1 m telescope could therefore cover the inner bulge in ~ 2 hrs, allowing for reasonably fast read out and pointing. Hence, stars could be monitored ~ 4 times per clear winter night. In the spring and fall, only 2 or 3 observations would be possible. This would be adequate to recognize and measure the short ~ 2 day events which are expected to be typical. Alternatively, one could achieve the same signal to noise on a 2 m telescope in only 150 s, implying that similar results could be obtained on a 2 m with a single 1024^2 array.

I now justify the estimate for the mean radius of a source star $\langle r_s \rangle \sim 22R_\odot$ made near the end of the last section to calculate the fraction of transit events. In the Raleigh-Jeans limit, the radius of a star scales $r_s \propto T^{-1/2}10^{-M_K/5}$, i.e., it is only weakly dependent on temperature, T . Adopting this framework, I estimate the stellar radius to be $r_s = 11 \times 10^{(13-K_0)/5}R_\odot$, where I have assumed that the source stars are a factor 0.7 cooler than the Sun, $M_{K,\odot} \sim 3.3$, and $R_0 = 8$ kpc. Then integrating over the K band luminosity function, I find $\langle r_s \rangle = 22 R_\odot$. Since, the Raleigh-Jeans limit does not strictly apply and since the brightest stars are actually cooler than I have assumed, the true value is somewhat higher.

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